Chapter 4: An Integrated Carbon Cycle Science Program

The previous two chapters of this report summarized our present understanding of the global carbon cycle and the basic questions that confront present-day efforts to better understand it. This chapter presents an integrated plan to achieve the major goals that have been identified:

Near-Term Goals of the U.S. Carbon Cycle Science Plan

Goal 1: Establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the underlying mechanisms that regulate it.

Goal 2: Establish accurate estimates of the oceanic carbon sink and the underlying mechanisms that regulate it.

Goal 3: Establish accurate estimates of the impact of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales.

Goal 4: Improve projections of future atmospheric concentrations of carbon dioxide through a combination of manipulative experiments and model development that incorporates appropriate biophysical and ecological mechanisms and carbon cycle-climate feedbacks into global climate and carbon cycle models.

Goal 5: Develop a scientific basis for evaluating potential management strategies for enhancing carbon sequestration in the environment and for capture/disposal strategies.

These goals are intended to guide research for the period of the next 5 to 10 years.

Two general hypotheses were also identified in Chapters 1 and 2 as those most critical for the U.S. Carbon Cycle Science Plan (CCSP) to address:

Hypothesis 1: There is a large terrestrial sink for anthropogenic CO_2 in the Northern Hemisphere.

Hypothesis 2: The oceanic inventory of anthropogenic CO_2 will continue to increase in response to rising atmospheric CO_2 concentrations, but the rate of increase will be modulated by changes in ocean circulation, biology, and chemistry.

The research program outlined here will ultimately be judged by its ability to provide practical answers to both scientific and societal questions. Scientists and policy makers must be able to evaluate alternative scenarios for future emissions from fossil fuels, effects of human land use, sequestration by carbon sinks, and responses of carbon cycling to potential climate change. Thus, a key motivation for further research is to develop the predictive capability to define responses of the global carbon cycle to change, as reflected in Goals 4 and 5.

Recent assessments of global environmental research have emphasized the need for programs that are both integrated and focused (e.g., National Research Council 1998). This plan puts forth a program that focuses on key problems, yet maintains breadth to reveal new problems and priorities in those areas where the knowledge needed to define focused strategies is currently lacking. In Chapter 6, this report also proposes a management structure for implementation of the research plan and the development of critical partnerships to ensure continuous reassessment and prioritization of goals.

Much recent progress in knowledge of the carbon cycle has resulted from studies at the global scale for time periods of years to decades. However, to make significant progress in understanding and quantifying the critical mechanisms that will determine future levels of atmospheric CO_2, data must also be obtained for specific geographic regions over a range of time scales. The fingerprints of dominant processes are to be found by studying regional carbon balances and temporal variability. Efforts to address both intermediate spatial scales and longer time scales are thus essential components of the proposed plan.

The program will also study the main processes influencing how carbon cycling may change in the future. These studies will be integrated in a rigorous and comprehensive effort to build and test models of carbon cycle change, evaluate and communicate uncertainties in alternative model simulations,and make these simulations available for public scrutiny and use. Clearly, the systematic incorporation of newly understood mechanisms in models must be accompanied by model integration using high-quality standard inputs and rigorous consistency tests against an array of benchmark data. Data management and data set construction are sometimes underrepresented in hypothesis-oriented programs. This pitfall must be avoided because,ultimately, it weakens the ability to test hypotheses using comprehensive data and to develop powerful generalizations and new hypotheses.

At its most basic level,the global carbon cycle must be viewed as a singular entity. Its various components are so interactive—over so many different scales of time and space—that they cannot conveniently be “isolated”for independent study or modeling. Data are most valuable when combined from a variety of measurements and methods associated with different carbon-cycle components; for example,when oceanic data are applied to help interpret results for the atmosphere and terrestrial biosphere,and vice versa. The present plan,then,proposes three different types of general approach:

- **Extend observations** over the important space and time scales of variability in all active carbon reservoirs
- **Develop manipulative experiments** to probe key mechanisms and their interactions
- **Integrate these data, analysis, and modeling approaches** so that they are mutually supportive and can be focused on key problems.

The observational strategy described in this chapter is designed to combine atmospheric measurements with observations from space, air, land, and sea to reveal specific processes that affect terrestrial and oceanic carbon exchange at regional as well as global scales. While the goal of the terrestrial component of this strategy is ultimately to understand the Northern Hemisphere terrestrial sink, the continent of North America is an excellent focus for the U.S. research community in developing this research objective. North American logistical capabilities are excellent and cost-effective, and there are extensive existing data sets for North American ecosystems, land use, soils,industrial activities, and history. Recent research has pointed to the particular importance of understanding terrestrial carbon exchange in the Northern Hemisphere, and North America’s large geopolitical units facilitate the development of an integrated continental analysis of carbon sources and sinks. Parallel research by European and Asian colleagues will be encouraged to expand the coverage into other parts of the Northern Hemisphere terrestrial biosphere.

Similarly, the northern oceans are relatively accessible, and a solid foundation of oceanic data and knowledge is available to support integration of studies of North American atmospheric CO_2 exchange with studies of CO_2 exchange in the oceanic regions adjacent to it. These foci offer a unique opportunity to combine atmospheric, oceanic,and terrestrial studies in a way that will constrain major components of the global CO_2 budget.

Goal 1: Understanding the Northern Hemisphere Terrestrial Carbon Sink

One principal goal of the CCSP is to establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the biophysical mechanisms that regulate this sink. Several major activities should be conducted in this area:

- An expanded program of atmospheric concentration measurements and modeling improvements in support of inverse calculations and global biogeochemical models
- A network of integrated terrestrial research sites with eddy-covariance flux measurements and associated process studies,manipulation experiments,and models, which as a whole are sufficient to reduce uncertainty about the current and future carbon cycle to acceptable limits.

The two boxes here summarize the specific proposed program elements,which are discussed in detail in the sections that follow.

Goal 1a: Atmospheric Measurements and Models—Major Program Elements and Activities

- Expand current atmospheric monitoring and observational networks to acquire—
  - Vertical concentration profiles in continentalsource/sink regions
  - Increased continuous measurements (as contrasted with weekly flask data) of CO_2 and associated tracers at selected continental surface stations
  - Flask measurements in undersampled regions, providing the data needed for continental and regional apportionment of net carbon exchange.
- Enhance the suite of measurements at the global network sites to include oxygen, carbon and oxygen isotopes, radon, and other parameters to constrain the locations and processes responsible for the carbon sources and sinks.

Goal 1a (continued)

- Conduct focused field campaigns over North America using aircraft sampling techniques in combination with improved atmospheric transport models and an enhanced flux tower network, to confirm and refine estimates of the magnitude of terrestrial sources and sinks of CO_2.

- Improve inverse models and strengthen connection between models and observations.

Goal 1b: Terrestrial Studies—Major Program Elements and Activities

- Synthesize results of recent and ongoing terrestrial carbon flux studies and use the data to constrain global carbon/terrestrial/atmosphere models.

- Conduct long-term monitoring of changes in above and belowground carbon stocks on forest, agriculture, and range lands using improved biometric inventories that explicitly address carbon issues, along with new types of remote sensing, to determine long-term changes in carbon stocks.

- Develop new technology to facilitate direct long-term flux measurements of CO_2, and install an expanded network of long-term flux measurements emphasizing the acquisition of data for representative ensembles of undisturbed, managed, and disturbed lands along major gradients of soils, land use history, and climate, and with a number of towers and sites sufficient to allow quantification of error in the spatial domain.

- Quantify mechanisms controlling terrestrial sources and sinks, their evolution in the geologically recent past, and the likely course of their evolution over the next decades to centuries. This quantification should be achieved through regionally nested sets of manipulation experiments, other process studies, and CO_2 flux measurements. Measurements should be integrated through a parallel set of nested models, with analyses scaled up to regions through use of regional inventory data.

- Conduct manipulations and focused process studies on ecosystem, local, and regional scales, coordinated with CO_2 flux measurements to quantify the mechanisms controlling terrestrial sources and sinks, their duration, and past and future evolution.

- Develop techniques for monitoring the dynamics of belowground carbon stocks.

Atmospheric Measurements and Modeling for Inverse Calculations

Atmospheric transport of CO_2 integrates the effects of local sources and sinks, with mixing around a latitude circle in a few weeks, and between hemispheres in about a year. A primary test of Northern Land Sink hypotheses requires resolving the longitudinal structure of the surface CO_2 flux, in addition to the variation in latitude. Clearly, the observations will have to define concentration gradients between the continents and the sea and between the planetary boundary layer and the middle and upper troposphere. These are inherently difficult measurements, because atmospheric mixing is so much more rapid around latitude circles than across them, and measurements near sources or sinks are highly variable. Design of the necessary atmospheric sampling program requires careful attention to the spatial and temporal distribution of sampling, the precision of the atmospheric data, and the details of some boundary-layer atmospheric processes that are not well understood at present.

The atmospheric observing system currently consists of roughly 100 sites around the world at which air is collected weekly in paired flasks for trace gas analysis at central laboratories, and few sites where observations are made continuously. The sites are intentionally located in remote marine locations to avoid local "contamination" by industrial or terrestrial emissions or uptake, and are operated at low cost using cooperative arrangements with volunteers. There are very few data acquired at altitude and at mid-continental stations.

To provide meaningful constraints on net terrestrial CO_2 exchange on the regional scale, the observing network will need to be strengthened considerably to characterize spatial and temporal variations associated with the carbon fluxes that need to be measured. The present network is designed to be insensitive to regional net exchanges. A recent evaluation of 10 global tracer transport models used for CO_2 inversions (Denning et al. 1999) found that the models converged when compared to the observed values for an inert tracer (SF_6) at flask stations in the remote marine boundary layer. However, they diverged where the data are sparse (aloft and over the continents). This problem is even worse for CO_2 due to the covariance between diurnal and seasonal cycles of CO_2 net exchange and rates of atmospheric mixing, often called the "rectifier effect." Expanding the atmospheric observing network to include routine sampling aloft, particularly over the continents, should be one of the highest priorities for the future. Atmospheric sampling over the terrestrial surface must include vertical profiles through a depth sufficient to capture most of the vertical mixing of the surface signal. At a minimum, this vertical sampling must span the depth of the planetary boundary layer (1 to 3 km in warm sunny weather). A primary research goal should be to determine first the optimal sampling density,

supporting measurements,and combination of continuous versus flask samples, for long-term airborne sampling. Multiple species,such as tracers of industrial activity, and isotopic ratios must also be measured to obtain the information needed to interpret the observations (e.g., Potosnak et al.1999).

The atmospheric boundary layer and the covariance between terrestrial ecosystem processes and near-surface turbulence are not resolved in most of the current generation of global atmospheric models. Most atmospheric tracer transport codes used for CO_2 inversion calculations represent subgrid scale vertical transport very crudely, if at all. Likewise, very few of these models include a diurnal cycle of CO_2 exchange.

However, even if a model could correctly represent the local covariance structure of the fluxes and the turbulence, the influence of the rectifier effect on the observed concentration field at remote flask stations depends on the persistence of the vertical gradient as the air is transported horizontally for hundreds or thousands of kilometers. This process is very poorly resolved in even the most detailed global models, and is not well understood theoretically.

A major effort in understanding the local forcing,spatial scaling,and long-distance transport aspects of the rectifier effect is required,through both observations and models. Testing the Northern Land Sink hypothesis also requires filling the gap at the crucial "middle scale"of the flux-transport-concentration problem. This middle scale between local and large-scale observations is completely missing from the current observing system and models.

The detailed design of the required atmospheric sampling program,which must be coordinated with design of the terrestrial flux network and ocean measurements proposed below, is a major scientific endeavor beyond the scope of this document. However some general requirements are clear. A strategy must be developed for atmospheric sampling over continental regions which takes into account the differences in ecosystem exchanges in stable and convective conditions. This variation must be explored over a range of ecosystems and meteorological regimes by sampling from eddy flux towers,tall towers, balloons,and light aircraft. Continuous long-term measurements of the vertical profile of CO_2 and other trace gases on tall transmission towers allows "representative" conditions to be defined for the planetary boundary layer (PBL) sampling at the local scale (Bakwin et al.1995, Bakwin et al.1998,Hurst et al.1997). Similar information can be obtained from continuous long-term measurements of CO_2 and other trace gases in conjunction with eddy-correlation fluxes defining rates of exchange between the surface layer and the planetary boundary layer (Potosnak et al.1999).Light aircraft can be instrumented with continuous analyzers to determine the boundary-layer budgets of trace gases over areas orders of magnitude larger than the footprint of an eddy flux tower (Desjardins et al.1997, Goulden et al.1998). These types of studies directly address the issues of scalability of tower fluxes,and can be used to design lower cost, routine sampling programs for larger scales.

Independent estimates of regional-scale carbon fluxes by inversion of atmospheric data will require a dense network of samples collected by light aircraft. Light aircraft sampling must be dense enough to capture meaningful gradients in surface fluxes, and must sample both within and above the convective boundary layer. Vertical profiles from light aircraft over a continental region could be coupled with high-altitude transects sampled from appropriately instrumented commercial aircraft (Marenco et al. 1998).

Both inversion calculations and forward models will benefit tremendously from additional constraints such as regionally detailed emissions data and multiple tracers. Samples should be analyzed for CO_2, as well as CO, CH_4, O_2/N_2, and stable isotopic ratios,all of which provide constraints on the carbon cycle. Ancillary data such as PBL structure (from wind profiling and traditional sounding systems),atmospheric transport (from four-dimensional data assimilation systems,4DDA),and the isotopic ratios of other components of the land-atmosphere system (plants, soils,precipitation,and groundwater) are needed. Such a system has been proposed using automated sampling equipment and rental aircraft (Tans et al.1996).

Regional observing and modeling programs have been proposed in other countries on a "campaign"basis,and the results of these studies can provide useful constraints on regional flux estimates using inverse modeling. Regional experiments quantifying carbon fluxes or tracer concentrations are currently underway or planned for the near future in Europe,Siberia,Brazil,and Australia.The design and implementation of U.S.observing systems and modeling programs should be optimized to take advantage of these complementary programs.

Ideally, inverse calculations of the carbon budget should subsume all available information,including flask samples,in situ data,aircraft sampling,air-sea flux measurements and eddy covariance data.Carbon budgets calculated from inverse methods should not, for example,be inconsistent with measured diurnal cycles of CO_2 data collected by regional sampling programs in other parts of the world. The current global observing system is so poorly constrained in the tropics, for example,that tropical fluxes are freely estimated in inversion models as a residual,allowing unacceptable freedom of terrestrial fluxes in higher latitudes without violating global mass balance.Inclusion of new regional data from experiments in Amazonia in these inverse models would provide stronger constraints on the carbon budget of North America, directly addressing uncertainties in the Northern Hemisphere Land Carbon Sink hypothesis.

New approaches to inverse modeling are needed to apply highly resolved atmospheric data to constrain regional fluxes. Atmospheric transport across regional areas is sufficiently rapid that concentration changes will have to be resolved on the order of hours to a few days rather than months or years. Trace gas transport will need to be represented at much higher spatial and temporal resolutions than at present,possibly using "observed" meteorological fields from four-dimensional data assimilation systems,or by incorporating carbon fluxes into models used in operational weather forecasting. Significant improvements in the land-surface parameterizations used in numerical weather prediction would be required.

An objective of the global observational and inverse modeling system should be to provide meaningful integral constraints on spatially extrapolated estimates of carbon fluxes derived by "upscaling" local fluxes using process-based models and remote sensing.These observing and modeling programs,described in the next section, would be extremely valuable in the context of top-down estimates of flux derived independently from the global observing program.

Terrestrial Observations, Experiments, and Models

Studies to refine understanding of terrestrial CO_2 exchange confront fundamental questions. What are the fluxes of carbon into today's ecosystems? Which systems are taking up how much carbon? What factors influence changes in past and contemporary ecosystem carbon storage (e.g.,CO_2 itself, nitrogen deposition,other pollutants, climate,management practices)? How has the rate of carbon storage changed in the past centuries and decades? What systems and management practices cause net losses or gains of carbon? How will fluxes and storage of carbon in the terrestrial biosphere change with changes in climate and the chemical composition of the atmosphere?

Studies of terrestrial carbon cycling must focus on systematic sampling strategies designed to characterize *quantitatively* essential processes and to reject or confirm specific hypotheses concerning responses along gradients of principal controlling factors. There are several current hypotheses concerning the particular ecosystems or processes that take up CO_2 in response to environmental change. For example, variations in temperature and soil moisture (Dai and Fung 1993), growing season length (Myneni et al. 1997), N availability (Holland et al. 1997), CO_2 fertilization (Friedlingstein et al. 1995), and forest regrowth (Turner et al. 1995) have all been suggested to be involved (see, e.g., Goulden et al. 1996, Fan et al. 1998). Although measurements along gradients are a powerful technique for assessing ecosystem responses in systematically different conditions, in practice the factors that determine the changes along the gradient are confounded to some degree. Thus, great care must be used in interpreting observations and experiments along gradients. In addition, the confounding of control variables, together with variability, means that significant replication must be obtained at least at some points along environmental gradients.

The role of land use must be a central subject in any plan for terrestrial carbon research. In the annual terrestrial CO_2 budget summarized above,it is evident that a significant portion of the terrestrial fluxes is related to present and/or past land use. Additional evidence from atmospheric and oceanic measurements suggests that most of the ~1.8 Gt C/yr land sink may be occurring in the Northern Hemisphere (Ciais et al.1995a). Some recent analyses suggest that an appreciable fraction of the total terrestrial sink may reside in North America (Fan et al. 1998,Rayner et al.1998). Inventory information is also accumulating to suggest significant sinks of carbon in North America,although the inventoried sinks are typically smaller than those suggested by the evidence from atmospheric measurements. The vast majority of land in the United States and southern Canada was disturbed in the past and is managed,intensively or extensively for human use. North American carbon sinks,as well as uptake by European or Asian ecosystems,are strongly affected by human activities. Studies of the role of land use history in determining the fluxes are discussed below in this chapter in section "Goal 3: Land Use."

A deliberate sampling and experimental design is required,aimed at characterizing fluxes and processes controlling carbon storage in forests, grasslands, agricultural lands and soils. The design should emphasize not the identification of "typical" sites for a vegetation regime,but the identification of a ***network*** of sites within vegetation types that sample the principal axes of variation. These axes of variation would include not only climate and soils (Schimel et al.1997),but also disturbance type and time since disturbance. A high priority is the development of new methods for measuring carbon fluxes belowground.

A principal focus of studies within this network would be systematic observation of carbon exchange fluxes along environmental gradients. This is now possible to an unprecedented degree. The key gradients (e.g., climate, nutrient deposition, forest age,plant functional types,land use) can be defined. Rates of carbon exchange can be measured. Previous efforts to estimate net CO_2 exchange have been hindered by pervasive small-scale heterogeneity in terrestrial carbon storage,and by difficulties in assessing changes in belowground carbon storage. Forest inventories represent a critical first step in quantifying storage, but they need to be upgraded to provide better information on carbon,coordinated to help scale results from flux stations and airborne regional measurements,and integrated to provide consistent, continental-scale estimates of net carbon exchange. Eddy flux data are providing high resolution on changes in carbon storage on the scale of hectares (e.g., Goulden et al. 1996, Goulden et al. 1998). However, further technological developments are needed to bring down costs and improve the accessibility of the technique and the reliability of the method. (Commercial development of the technology now appears to be underway.) Finally, hectare- to kilometer-scale-resolution data can be extrapolated to regional (and ultimately global) domains using advanced remote-sensing techniques and verified through expanded atmospheric concentration measurements and models described earlier in this chapter.

A network of flux measurements along well-defined environmental gradients provides several valuable products. Fluxes can be directly extrapolated using area weighting from remote-sensing and inventory information. Flux observations can provide information about responses to environmental forcing (such as temperature and soil moisture). Better understanding of the response to environmental forcing can then be used in extrapolations and analysis. Flux measurements allow estimates of carbon sequestration from inventories to be compared to measured carbon uptake. Fluxes can also be extrapolated using models. Estimates of seasonal or interannual variations in fluxes can be compared to changes inferred from atmospheric measurements. Applying this approach to temporal variations is especially important. For example, while interannual variations in local climate and carbon fluxes may suggest hypotheses about large-scale regulation, they provide limited insight without direct large-scale mass-balance constraints. Conversely, estimates of the large-scale atmospheric CO_2 seasonal cycle and sources and sinks provide a vital global constraint on models. However, these estimates provide limited information about the modeled mechanisms and sensitivity without greater spatial resolution and precision in estimated fluxes.

The ability to apply eddy-covariance flux measurements to regions will be limited by knowledge of errors in both temporal and spatial scales. Because the technique accumulates data at high frequency, there is essentially little problem in the temporal resolution of the specific measurements. It is critical, however, that the variability of NEP over seasons and years be captured by continuous, high-quality operation of each of the sites. It is in the spatial domain that problems with regional measures of NEP using the eddy-covariance flux method may arise. A region (or biome) can be thought of as a unit of observation from which samples can be drawn to allow the region to be characterized quantitatively with explicit statements of error for NEP in space. This characterization can be achieved if eddy-covariance measurements are replicated within regions, not only across the axis of a particular gradient (as discussed above) but also normal to the gradient axis in order to quantify variance at each gradient level. The number of replications needed cannot be stated a priority as it is itself a research issue. Nevertheless, adequate replication is absolutely essential to providing information that ultimately can be used to reduce uncertainty in estimates of current and future regional carbon flux and storage. Such replication may depend to a large degree on the development of low-cost, stable, reliable, semiautomated instrument packages that will greatly reduce the manpower and logistical costs associated with the measurements.

The envisioned approach would combine process studies and experiments (designed to increase basic knowledge and improve predictive models) with flux measurements designed to allow models to be tested. A well-designed network of study sites would serve as a focal point for many different types of research. Process studies on nutrient interactions, on feedbacks from species diversity and changes to biogeochemistry, and on climate effects are all needed. Experimental manipulations can help untangle complex mechanisms and test hypotheses for ecosystem responses to conditions outside the current envelope. For example, studies using preindustrial CO_2 levels can yield critical information on carbon storage from past changes. Studies manipulating CO_2, nitrogen deposition, and climate at sites at a range of times since disturbance are crucial for quantifying interactions among these key global change drivers. It is essential that the research network use common approaches and methods with the highest degree of standardization of methods and instruments as possible. Particular attention must be given to quality assurance in the operation of monitoring equipment and conduct of manipulation experiments. Formal protocols will certainly be required at an early stage. Recognizing that new and better methods and instruments will be developed, the networks need to be able to accommodate innovations so that the innovations can be applied across the entire system, not piecemeal.

The United States and other nations already invest significantly in natural resource inventories for management purposes. These inventories should be designed to provide better information on carbon. Only large-scale operational inventories—such as those maintained by government agencies—can provide data from the hundreds to thousands of sites needed for direct spatial integration. The inventory data need to be more effectively integrated with other sources of information, including eddy flux and remote sensing. In addition, it is critical to extend the inventory approach to cover the fate of carbon after it is harvested from forests. This carbon includes not only logging residues, but also manufactured products and waste streams.

Finally, eddy-covariance flux time-series are needed to provide closure on carbon budgets at key sites, to measure CO_2 uptake or loss as a function of the location in the experimental design.

The proposed terrestrial carbon research network poses several significant challenges. For measurements along gradients to have power in rejecting hypotheses or parameterizing models,large sample sizes are required. Today's networks of flux sites number in the tens of installations. Globally this approach will require significantly more measurement sites,an arrangement that requires significant prior investment in autonomous measurement technology and theory to make the technique simpler, more robust,and less expensive. The program must be sustained for a significant period,because the measurements become valuable only when reasonably long time-series have been collected,and they will become more valuable over time.

Clearly, both the design of the initial network and its implementation will also require extraordinary care,statistical rigor, and investment in technology. Enormous resources could be expended on process studies, experiments, flux measurements,and inventories *without* materially reducing uncertainty about either today's CO_2 budget or simulations of future trends. For the nation's scientific resources to be efficiently deployed,an initial synthesis and analysis of existing in situ data (including soil and sediment surveys, forest inventories,and observations at existing Long-Term Ecological Research [LTER] and AmeriFlux sites (LTER maintained by the National Science Foundation and AmeriFlux maintained by the Department of Energy, National Aeronautics and Space Administration,and National Oceanic and Atmospheric Administration), remote sensing,and model results is needed to define patterns of variability. Then,the research community must be engaged in the effort to use this synthesis as a basis for site selection in a network designed to understand patterns at large scales.

Once an analysis of existing data and models is done, a critical set of measurements and experiments can be designed to efficiently sample the space identified. Different sets of measurements may be appropriate for different suites of sites. The design should take advantage of remote observations of land cover and land cover change, which are quite comprehensive for the United States. Similarly, inventory data are already available,and with system and data management upgrades,management data may be made highly useful. With some effort in technology and theory development,the present network of roughly 20 flux measurement sites can be increased by a factor of 2 to 10.

Six other types of studies are proposed to complement the proposed flux measurements at network sites:

1. **Experimental manipulations of CO_2, temperature, nitrogen,and other key controlling factors.** Manipulations are an ongoing line of research that must be enhanced. A number of specific questions about the nature,quantitative importance,and persistence of mechanisms driving the current terrestrial carbon sink can be best addressed through direct experimentation. Manipulations including ecosystem-scale climate change,nitrogen additions,and elevated or decreased CO_2 can provide critical insights on interactions,on responses to conditions in the past or the future,on ecosystem-to-ecosystem variation in responses,and on interactions with other anthropogenic impacts,including harvesting,other land use change,biological invasions,and altered biological diversity.

   The next generation of manipulative experiments designed to understand and quantify the current terrestrial sink should emphasize processes at the ecosystem scale,including responses of both biogeochemistry and ecological dynamics. Studies with preindustrial CO_2 are critical, but will require new technologies,especially for experiments at the ecosystem scale. Experiments to quantify effects of multiple factors, alone and in combination,are also crucial. Currently, we have little idea of the extent to which the carbon sink in forest regrowth includes signals from increasing CO_2, N deposition, or climate change. Similarly, we have no idea of the consequences for carbon storage of vegetation changes, for example,increasing shrub abundance in many of the world's grasslands (Archer et al. 1995). Experiments could be used to probe both the drivers and the consequences of vegetation changes,especially experiments on ecosystems where the transitions can occur quickly.

   The next generation of experiments should also include pilot studies to evaluate deliberate carbon sequestration strategies. Issues concerning the limited spatial and temporal scale of manipulative experiments should receive intensive attention,so that lessons from the experiments can be effectively interpreted and incorporated into global-scale models.

2. **Long-term terrestrial observations.** Expansion and enhancement of the LTER network will pay huge dividends by defining the ecological and current and historical land use factors that regulate sequestration and release of carbon from major ecosystems. The network expansion is envisioned to provide new sites, roughly equal in number to the roughly 20 currently existing,strategically located to examine ecotones, or boundary zones between regions with different vegetations or biomes,likely to play a significant role in regulating global CO_2. Enhancements are needed in two dimensions. Quantitative,ecosystem-level work on carbon stores and turnover should become a major component of each site, and LTERs should become key points for large-scale manipulations and for the expanded flux network. By doubling the budget and number of sites in the current network, and adding important new research tasks, there should be a strong synergy between the carbon focus and present ecological and process-oriented goals of the LTERs, enhancing both.

3. **Intensified flux measurements at sites where detailed process studies are coordinated with eddy-covariance measurements.** Intensive observational studies can be conducted where carbon uptake and many of its controls (N availability, soil moisture, microclimate, light) and mediating variables (Rubisco content of leaves, conductance, stem flow, belowground processes) are measured. In essence, such studies allow natural spatial and temporal variability to perform the experiments that test hypotheses. Hypothesized control processes can be evaluated if a suitable suite of associated measurements (climatic, atmospheric, and biological) is made. These studies share some of the advantages and disadvantages of deliberate manipulations. The major advantage is that the perturbations are "natural," including all time scales. The disadvantage is that the conditions are not under control of the experimenter. This "natural approach" is that followed by the present AmeriFlux network.

4. **Flux scaling studies in which tall towers, boundary layer measurements (Convective boundary layer budgets) and aircraft profiles address the scaling of land surface fluxes to their signatures in the atmosphere.** Opportunistic use should be made of tall transmission towers (e.g., Bakwin et al. 1995), which allow micrometeorological fluxes to be determined over much larger footprints than typical canopy towers. Additionally, tall towers allow the vertical profile of the eddy flux to be measured, testing scaling strategies by varying the footprint of the measurement. With appropriate inclusion of meteorological data collection (radar wind profilers or balloon sondes), tall towers also allow the direct measurement of the local forcing of the atmospheric CO_2 rectifier effect, which will facilitate larger scale atmospheric modeling. Aircraft observing campaigns should use eddy-covariance sites as anchor points. These programs can be designed to provide flux estimates over a much larger footprint than that of even a tall flux tower, through measurements of continental boundary layer budgets for scales of several tens of kilometers (Chou 1999, Desjardins et al. 1997, Lloyd et al. 1996) to transects measured by flux aircraft for scales of tens to hundreds of kilometers (ABLE-2/3 experiments, BOREAS, FIFE[2]). These data allow a quantitative evaluation of the relationship among intensive flux measurements, land surface cover, and ancillary process data; and would facilitate the development of scaling strategies by providing spatially extensive snapshots as context.

5. **Remote sensing of terrestrial properties.** Remote sensing must be a critical component of any plan for terrestrial carbon research. Efforts to characterize terrestrial carbon cycling should exploit interaction with programs such as the World Climate Research Program's Global Energy and Water Cycle Experiment Continental Scale International Project (GEWEX/GCIP). This program has already demonstrated success in integrating remotely sensed and in situ measurements of energy and water fluxes. To the extent possible, carbon research plans should be structured so that they can take advantage of improved satellite data products expected in the near future. These products will include new 30-meter Landsat Thematic Mapper-derived land cover data, high-resolution data sets expected in association with the ETA Mesoscale Model, and data products anticipated from the Mission to Planet Earth. Of particular interest is the possible application of advanced algorithms to the upcoming Earth Observing System (EOS) sensors to derive plant canopy functional properties.

6. **Integration of observations with model development.** Understanding terrestrial processes requires that ongoing observations be linked to the continued development and testing of models. It is extremely difficult to develop terrestrial carbon models that include state-of-the-art process representations for all of the needed processes on multiple temporal and spatial scales. Often the limitations of models serve as signposts in formulating and testing new hypotheses. Examples of current model frontiers are the effects of CO_2 on a full suite of plant processes (including allocation of carbon to different parts of a plant), dynamic interactions between carbon and nitrogen budgets, hydrologic changes (such as drying or thawing of boreal peat), and vegetation dynamics such as successional changes over long time scales. Models must also be improved to systematically incorporate information about human and natural disturbance of the land surface. Current models emphasize physiological and biogeochemical processes and largely neglect the carbon storage dynamics induced by cultivation, forest harvest, fire, fire suppression, and other intensive disturbances as well as biological invasions, changes in biological diversity, and other ecological processes

The chief requirement for the progress of modeling—particularly in hypothesis testing—is better integration of models and data. Model development is currently supported by a variety of programs, including NOAA Carbon Modeling Consortium (CMC), Terrestrial Ecology and Global Change program (TECO), Vegetation/Ecosystem Modeling and Analysis project (VEMAP), NSF's Methods and Models for Integrated Assessment (MMIA), and numerous disciplinary programs. Although this diverse range of support encourages innovations, more effort is needed in integration. The assembly of observational data into

[2] Atmospheric Boundary Layer (ABLE); BOReal Ecosystem-Atmosphere Study (BOREAS); First ISCLIP (International Satellite Land Surface Climatology program) Field Experiment (FIFE)

Photograph of the 447-meter tall WLEF-TV transmitter tower, Park Falls, Wisconsin. The tower is owned by the State of Wisconsin Educational Communications Board, and is being used for measurements of CO_2 mixing ratios (see Bakwin et al., 1998) and atmosphere/surface exchange of CO_2 by eddy covariance. Transmitter towers up to 610 meters tall are located in many areas of the USA.

standard forms that can be used by models is a significant integrative task,without which rigorous testing and comparison of models cannot be achieved. Thus, very different models may appear to have equal "validity," incorrect hypotheses may not be rejected,and the improvement of models and hypotheses may be inhibited. Standard data sets are urgently required for terrestrial model input (climate,soils,disturbance regimes,N deposition) at regional and global scales. Without these standardized inputs, model intercomparisons are meaningless. Standard data sets must be assembled in ways that are compatible with all models simulating particular processes and scales. There is ample precedent for this approach. In meteorology, the production of reanalysis data sets has resulted in long time series of physical variables that are critical in evaluating climate models. These data sets might be valuable as climate inputs to carbon models,but they must be checked for consistency with known carbon-energy-water relationships.

Recent Intergovernmental Panel on Climate Change (IPCC) intercomparisons of global carbon-cycle models were made only after all the models were required to meet consistency criteria based on input of a standard set of historical atmospheric CO_2 and emissions data. Clearly, the systematic incorporation of newly understood mechanisms in terrestrial models must be accompanied by model integration using high-quality standard inputs and rigorous consistency tests against an array of benchmark data.

The implementation of the terrestrial studies described above might proceed as follows:

- An analysis of existing spatial data, model results,and remote-sensing products must be initiated as a basis for an experimental and observing system design that will allow the testing of hypotheses and the extrapolation of site-specific studies. A working group with modest funding should be assembled to undertake this activity. The project should assess the U.S.data, results and products in detail and global information at lower resolution.
- The nation's forest, agricultural,and aquatic monitoring programs should be evaluated with the goal of identifying low-cost/high-leverage enhancements to the existing programs. Collaboration among agency scientists and managers and the broader carbon science community is crucial.
- Flux measurements are an essential part of the program,because they may provide closure on carbon and water budgets,which is difficult with conventional sampling,especially closure on belowground fluxes. However, there are problems with the existing technology and theory. Resources need to be invested to reduce uncertainties in measuring nighttime fluxes, allow use in more complex terrain,and develop cheaper and more autonomous systems. Effort needs to be directed toward developing a rigorous statistical approach to placement of sites for atmospheric monitoring and manipulation experiments.
- A continued effort is needed on modeling,on the integration of new experimental knowledge into models, and on sustained testing of models in increasingly rigorous model-data comparisons. Models are required both for the integration of knowledge about the present,and for prediction of the response of systems to future changes.
- Enhanced manipulative experiments at the ecosystem scale are critical for exploring ecosystem responses to environmental conditions outside the current envelope and for assessing responses to interactions among climate,ecological processes,and anthropogenic changes. Manipulative experiments should be designed to support model development, facilitate scaling in space and time, evaluate proposals for managed carbon sequestration,and enhance broad communication about the role of the terrestrial biosphere in the global carbon cycle.
- Long-term ecological research,with greater emphasis on carbon-related issues,will provide the critical data on ecological and land use historical factors regulating sequestration of carbon.

Goal 2: Understanding the Ocean Carbon Sink

Long-term goals for CO_2 research in the ocean are, first, to quantify the uptake of anthropogenic CO_2 by the ocean,including its interannual variability and spatial distribution;and,second,to understand and model the processes that control the ocean's uptake of CO_2. Uptake of anthropogenic CO_2 can be quantified by measuring either the flux itself or the resulting change in carbon inventory. Both should be carried out,with a strong emphasis on disaggregating the global uptake into contributions from major ocean regions and monitoring temporal variability. The process and modeling goals can be attained by research on the rate-limiting steps for uptake, the causes of spatial and temporal variability, and the better integration of models with data to predict long-term trends. These goals are similar to those for the terrestrial environment,but the major research challenges are distinct. Goals in understanding the ocean carbon sink are the following:

- Develop new technology to facilitate systematic and lower cost long-term observations
- Carry out air-sea carbon flux measurements with a near-term focus on the North Atlantic and North Pacific,to coordinate and integrate results most closely with the terrestrial research on the Northern Hemisphere and tropics

- **Conduct global surveys of oceanic inventories of fossil CO_2 along with relevant tracers,including their evolution with time,in support of inverse calculations and global models of carbon uptake**
- **Realize studies of the physical and biogeochemical processes controlling the air-sea flux of carbon in the oceans,including manipulation experiments and development of models.**

The following bullets summarize the proposed program elements.

Goal 2: Major Program Elements and Activities

a. Required new technology

- Instruments for measurement of CO_2 and related quantities on moorings, drifters, and towed vertical samplers
- Rapid water sampling techniques
- High throughput multi-element analyzers for shipboard carbon system measurements (of dissolved inorganic carbon [DIC], dissolved organic matter, particulate organic matter, alkalinity, temperature, salinity, nutrients, O_2,) and related tracers (CFC's, ^{14}C, ^{13}C, etc).

b. Air-sea carbon fluxes

- Apply new technology to install an expanded network of long-term stations, drifters, and underway measurements, emphasizing acquisition of data for representative ensembles of oceanic regions and conditions, to define by observation the spatial distribution and temporal variability of the air-sea flux.
- Conduct focused field campaigns at basin scale over both the Pacific and Atlantic using aircraft sampling combined with shipboard and ground-based measurements and improved atmospheric transport models. The goal is to confirm and refine estimates of the magnitude of oceanic sources and sinks of CO_2 from pCO_2 (partial pressure of carbon dioxide) data, and to provide the tools and data necessary for improved inverse model estimates of Northern Hemisphere terrestrial sinks.

c. Oceanic inventory measurements

- Synthesize results of recent global ocean carbon surveys in support of global carbon/ocean/atmosphere inverse and predictive model development and planning for future global surveys.
- Initiate ongoing program to repeat global CO_2 and tracer surveys every 10 to15 years to monitor the oceanic CO_2 inventory and its evolution in space and time.

d. Process studies, models, and synthesis

- Vigorously pursue ocean process studies, including manipulative experiments, to improve mechanistic understanding of processes controlling carbon uptake and their sensitivity to climate. This research includes direct measurements of air-sea flux of CO_2, factors regulating biological fluxes, and large-scale tracer release and tracking experiments to define quantitatively the controls on uptake of anthropogenic carbon by the oceans.
- Develop improved models of physical, chemical, and biological processes to analyze process observations and to project how these processes may affect ocean uptake of CO_2 in the future.
- Develop new basin and global ocean carbon cycle predictive and inverse models, including improved process models, to analyze air-sea flux and ocean carbon inventory and tracer observations and to project future ocean uptake of CO_2.
- Develop the use of remote-sensing tools for ocean monitoring of physical and biological properties to gain mechanistic insight and to extrapolate local observations to larger scales.

Until recently, the primary tool used for studying the oceanic uptake of anthropogenic carbon has been models validated with observations of tracers,particularly the distribution of natural and bomb radiocarbon. The absence of carbon measurements to verify model estimates has been a serious limitation in testing our understanding of oceanic uptake. Recent improvements in the precision of measurements of DIC and associated tracers such as O_2 have given us greatly increased confidence in estimating the inventory of anthropogenic carbon directly from DIC. New techniques discussed in Chapter 2 allow filtering out the background DIC concentration and the effects of seasonal and interannual variability. These achievements make it possible to detect the total anthropogenic inventory and its change over time scales on the order of a decade. The measurements are also being used to estimate transport of carbon across sections in ocean basins. Both the tracer-based modeling approach and the inventory method will continue to be important tools in monitoring the oceanic uptake of anthropogenic carbon.

Nevertheless,neither modeling nor the inventory approach can give us the air-sea flux of CO_2 at a given time and place. These methods are thus of limited use in

determining the annual and interannual variability of the carbon cycle,and in constraining inverse models of atmospheric observations. However, such spatial and temporal resolution is required for atmospheric inversions to detect the Northern Land Sink as well as to better understand the processes that control the air-sea flux of carbon and its variation in time. The best way to obtain adequate spatial and temporal resolution is by measuring the air-sea flux. This can be done either directly using techniques that were recently tested successfully for the first time at sea,or indirectly using measurements of ΔpCO_2 multiplied by an estimate of the gas exchange coefficient. The direct technique,though,does not lend itself to the large number of measurements that would be necessary to obtain adequate temporal and spatial resolution. Its primary application will be in the essential task of improving our understanding of air-sea flux processes. The indirect measurement technique is the most promising for obtaining the time-dependent air-sea flux over a given period of time and region of the ocean. The application of the indirect flux measurement technique faces formidable obstacles,as discussed in Chapter 2. However, recent progress in techniques for measuring ΔpCO_2 and in our understanding of gas exchange and ability to study it gives cause for optimism that air-sea flux measurements will contribute significantly to our understanding of the global carbon cycle over the next decade.

In conjunction with measurements of the air-sea flux and ocean carbon inventory, it is essential to study the physical and biogeochemical processes that control the air-sea flux and its spatial and temporal variability. It is not sufficient to know within rough bounds the global rate of carbon uptake. Simulations of climate change show significant warming of the surface low latitudes as well as freshening of the high latitudes. These trends would increase the vertical stratification and have a major impact on ocean circulation. It is very likely that these changes will have a major impact on the transport of carbon from the surface ocean to the abyss,as well as affecting the biological pump. Projections of future trends in atmospheric CO_2 must be based on an adequate understanding of relevant oceanic processes and the incorporation of this understanding into models. Considerable work remains to be done in these areas,building on the promise demonstrated by recent progress.

The identified program elements are discussed in more detail in the following subsections.

Needed New Technology

The processes that control carbon cycling in the ocean exhibit large spatial variance,which itself is not stationary, but changes significantly on diurnal,seasonal,annual, decadal,and even longer time scales. Comprehensive spatial and temporal coverage would be very expensive to obtain with dedicated global measurement programs using current methods. It is very important to assure the development of lower cost,more efficient methods for collecting water samples and making at-sea measurements of the carbon system (dissolved inorganic carbon,dissolved organic matter, particulate organic matter, alkalinity, T, S, nutrients, O_2, and related tracers such as CFC's, ^{14}C, etc). A major need also exists for the continued provision of high-quality DIC standards,which was a major element in the success of the World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS) carbon measurement program. Standards should be developed for other important tracers as well,with particular importance attached to carbon isotopes and nutrients.

Autonomous measurement capability for carbon system parameters is also strongly needed. Time-series measurements are presently limited to locations near island ports such as Bermuda and Hawaii. The present U.S.ocean carbon-cycle time-series stations at Hawaii and Bermuda are run at an annual cost of about $1 million each. Activities supported by the operating budgets include studies of the processes affecting the carbon cycle as well as monitoring of the carbon cycle per se. Significant improvements in the coverage and the economics of the carbon cycle monitoring component of the present activities are possible. The scientific community presently has the technical capability to deploy instruments for measuring the air-sea difference of pCO_2 on commercial and research ships. There has been initial success in deploying reliable instruments on autonomous buoys (Friederich et al.1995). Further technical developments may allow the addition of in situ monitoring of related variables such as nutrients and oxygen.

A major program of technological development is an essential component of ocean carbon research over the next 5 years.

Air-Sea Carbon Fluxes

We recommend the following programs to characterize the climatological uptake of CO_2 by the oceans,the geographic distribution of uptake of CO_2, and, eventually, its interannual variability.

Time Series Observations. The air-sea flux of CO_2 is extraordinarily variable in space and time due to changes in circulation,temperature,and salinity, as well as biology. The key to determining this flux and understanding its variations is continuous in situ monitoring,including both time-series stations and regular measurements along transects using ships of opportunity.

Temporal variations in some areas,such as the Equatorial Pacific,have been identified as major causes of variability in air-sea CO_2 exchange. Existing time-series studies are located mostly in the subtropical ocean gyres, while there are major gaps in data on regions of active ocean mixing and high biological variability, especially in subpolar and polar latitudes. Temporal variability is greatest in surface and subsurface layers,locations where biological and physical feedbacks are most likely to alter the ocean's ability to absorb CO_2. Characterization and understanding of temporal variance is a prerequisite for understanding the processes that limit rates of ocean CO_2 uptake.

Moored and underway time-series observations should, whenever possible, map a range of properties associated with biological productivity. Extending measurements beyond pCO_2, temperature, and salinity (for example) can give both rate and process information about biological productivity. Concentration measurements of CO_2 and nutrients are valuable in this regard. Precise measurements of O_2 concentrations in the mixed layer, coupled where possible with measurements of inert gas concentrations and wind speed, yield information on net production and ventilation. The measurement of isotopic properties gives rate information of interest: the $\delta^{13}C$ of CO_2 constrains net production (Zhang and Quay 1997), while the triple isotope measurement of dissolved O_2 constrains gross production (Luz et al. 1999). Measurements of atmospheric O_2 concentration give valuable information about instantaneous and annually averaged ocean carbon fluxes. Ongoing flask sampling can reflect interannual variability and long-term trends in ocean carbon fluxes. Continuous concentration measurements,now becoming possible, should be developed and used for more detailed studies.

Focused Field Campaigns. An important lesson of carbon cycle research has been how much knowledge of one carbon cycle component depends on knowledge of others. One of the major constraints on the magnitude of the terrestrial sink and its spatial distribution has been knowledge of the air-sea carbon flux and its spatial distribution. In particular, addressing the Northern Land Sink hypothesis will require focused field campaigns over both the North Atlantic and North Pacific to estimate the air-sea flux of carbon during the time terrestrial fluxes are analyzed. These campaigns should include aircraft sampling as well as shipboard and autonomous measurements, and will require improved atmospheric transport models for analysis.

Future field campaigns should focus on areas of critical importance to our understanding of the global carbon cycle. In particular, the Southern Ocean air-sea flux is presently poorly constrained and its temporal variability is unknown.

Oceanic Inventory Measurements

We recommend two programs to characterize the oceanic inventory of fossil CO_2 and its evolution over time:

Thorough analysis of recent ocean carbon observations. At present,the most robust constraint on ocean uptake of CO_2 comes from surveys and time-series of carbon system measurements carried out with instruments and methods now available and analyzed by techniques like those discussed in Chapter 2. Essential complementary measurements include those of carbon isotopes,the standard hydrographic and nutrient measurements,and transient tracers of ocean circulation. These surveys and time-series measurements provide direct in situ constraints on ocean CO_2 uptake that additionally provide strong constraints on the role of the terrestrial biosphere in the global carbon budget.

Over the past decade,the WOCE/JGOFS programs have provided an invaluable baseline on the current state of the ocean that will be useful for assessing future changes. Unquestionably, however, survey and time-series measurements must continue beyond the WOCE/JGOFS era to answer fundamental questions,such as whether oceanic CO_2 uptake is increasing or decreasing globally in the future. Such work is the analogue of the current network of atmospheric measurements,but substantially more difficult to implement. To plan the best possible program of continuing ocean observations,needed spatial resolutions must be determined,along with which variables to measure at what accuracy. A high priority over the next few years must be to use the current vastly increased oceanic data set to answer these questions and to design an optimal survey program.

Monitoring the evolving fossil CO_2 inventory in the oceans along with related tracers. Monitoring the evolving fossil CO_2 inventory is an essential long-term component of any effort to understand oceanic CO_2 exchange. Because the costs of conducting comprehensive surveys are presently very high, we propose that the needed measurements be accomplished through a reduced-level but continuous effort rather than the global "snapshot"paradigm of previous expeditions. This activity would be an ongoing and focused on specific limited areas each year. The goal would be to cover the entire world every 10 to 15 years. This approach would cost less per year and would assure maintenance of the required measurement expertise and capability for the long term. The ongoing survey could exploit strong linkages with other efforts such as CLIVAR (Climate Variability and Predictability programme) and GCOS (Global Climate Observing System) to make efficient use of ship time. It is thus critical to ensure that tracers relevant to the carbon cycle (e.g.,DIC,O_2, temperature,salinity) are covered in programs like CLIVAR that have the goal to monitor temporal trends in ocean properties.

The measurement suite should include total alkalinity and should frequently include a third CO_2-system property such as pH to assure internal consistency. The measurement of ^{13}C and TOC [total organic carbon] are essential, as are the development and use of standards. Measurements should include transient tracers,which provide temporal information about ocean mixing and water mass history that is essential to interpreting fossil CO_2 distributions. Finally, they should include bioactive chemicals such as iron whose oceanic distribution is poorly known but is likely an important influence on ocean carbon fluxes.

A complementary approach exploits the fact that the invasion of anthropogenic CO_2 into the ocean looks,in aggregate,like a vertical transport problem that can be effectively attacked through studies of the distribution of transient tracers. Various tracers are now available to span a variety of mixing scales (^3H/^3He, ^{14}C,CFC-12,SF_6, HFCs). Some of these tracers reveal mixing over the critical longer (decadal and century) time scales;and some help identify current short-term invasion rates for comparison with older data. Large-scale tracer release experiments provide an independent means to assess vertical transport rates and mechanisms. Likewise,direct eddy flux measurements are just starting to become available to test parameterizations of air-sea exchange.

Process Studies, Models, and Synthesis

We recommend the following four programs:

Selected studies of processes that control the mechanisms and rates of air-sea CO_2 exchange, vertical transport within the seas, and cycling of DIC and alkalinity. Ocean process studies yield understanding of the basic mechanisms controlling the ocean carbon cycle. Process submodels are also required in models of the time-dependent air-sea flux. Ideally, process studies and observational systems should be linked as intimately as possible to help determine the response of ocean carbon fluxes to interannual variability in climate forcing,and to identify feedback mechanisms. Some important processes that need to be studied are gas exchange and the physical processes that determine the rate of anthropogenic carbon transport from the mixed layer into the thermocline and deep ocean. Also important is the role of biological processes in determining the spatial and temporal variability of air-sea fluxes and anthropogenic carbon uptake. A major issue is the sensitivity of physical transport and biological processes to ocean properties that are likely to change with climate change. Knowledge of seasonal and interannual variability as well as direct manipulation experiments will be an important source of information. A deeper understanding of what controls the biological pump in the ocean is required,including the role of micronutrients such as iron and zinc,whose input to the ocean may be affected by climate,land use,or pollution. Program oversight must assure that priority is given to studies that can make a genuine contribution to understanding future atmospheric CO_2 levels.

One challenge is characterizing marine ecosystems well enough to model their effects quantitatively on air-sea carbon fluxes. Process studies include direct manipulation of the environment,such as the large-scale iron enrichment studies (Coale et al.1996),as well as systematic observations of the effects of "natural experiments," such as El Niño. Process studies,and in particular ecosystem-level manipulations (along the lines of the recent iron fertilization studies) should be used to evaluate the host of biological mechanisms proposed as potential feedbacks on ocean carbon uptake (Denman et al.1996). Possible feedbacks that can be tested include modifications of iron fertilization rates of HNLC (high-nutrient,low-chlorophyll) regions,particularly in the Southern Ocean;subtropical nitrogen fixation rates;Redfield carbon to nutrient ratios of export material;community allocation of sinking versus suspended/dissolved material;calcification rates;and subsurface remineralization depth scales. The effects of coastal eutrophication and elevated UV radiation have also been hypothesized as significant,but are rather poorly constrained.

An emerging research theme is the relationship between ecosystem structure and the export flux of carbon. Ecosystems dominated by the microbial loop recycle carbon efficiently and show very little export of carbon, whereas other regions dominated by diatoms and other large phytoplankton tend to show a large carbon export. It is important to understand how changes in ocean stratification and circulation in response to changes in climate will affect the ecosystem structure and uptake of anthropogenic carbon.

Improved process models. Mathematical models are required to express the relationships between physical forcing and biogeochemical processes,to evaluate the implications of results and observations for upper ocean pCO_2 variations and ocean carbon uptake. Seasonally resolved models of the circulation and physical properties of the upper ocean will improve the ability to take into account the influence of temperature,salinity, and transport on sea surface pCO_2. To consider interannual and longer term variability, as well as the effects of climate change,is essential to explore how changes in sea surface temperature,ocean circulation,stratification,and sea ice formation all affect the atmosphere-ocean balance of carbon. Biological models embedded into models of physical circulation will help further explain the large role that seasonally and interannually forced biological processes play in regulating upper ocean chemistry and CO_2 partial pressure in the mixed layer. Models with sufficient resolution to simulate meso-scale processes will be needed to study interactions that determine many of the ecosystem processes. A close collaboration with physical oceanographers studying ocean variability is an essential component of this program.

Improved basin and global carbon cycle models. A new generation of models must be developed for long-term projections of carbon uptake,integrated with the observations to allow data to be assimilated and to test the models. Conversely, models must be able to simulate the distribution of important quantities that can be tested in the field and must otherwise help in designing field experiments. For example,because variability in ocean hydrographic structure and ocean carbon cycling is in most instances associated with circulation changes, variations of carbon and hydrographic parameters will be correlated. An analysis that does not account for this covariance can be seriously in error, and a model that does not simulate the observed covariance will be wrong. Such problems will require a synthesis activity involving both model simulations and measurements. Program structures must be implemented to force both modelers and experimenters to make this integration happen.

Remote-sensing observations and numerical models are a natural marriage inasmuch as ocean in situ observations are often too sparse to initiate or validate model fields. Satellite data are often better matched to the time and space scales of models,but satellites generally measure only very simple indices of biological and physical processes and distributions. Thus,models are necessary to extrapolate simple satellite indices to more complex biological and physical processes and distributions consistent with the accuracy provided by in situ measurements and as required for carbon cycle research.

Remote sensing of ocean conditions and processes. Remote sensing is an important tool for extrapolating measurements and calculations in time and space and for providing estimates of key environmental parameter values needed by coupled physical and biogeochemical ocean models. Remote-sensing observations can also provide critical information during process studies and large-scale manipulation experiments.

One important application of satellite data is to relate the CO_2 transfer velocity across the air-sea interface to "sea surface roughness"on ocean-basin scales. Accumulated evidence suggests that estimates of wind velocity alone are not sufficient to estimate transfer velocity, owing to other factors that also influence surface roughness. These factors include the sea surface wave spectrum and resulting surface renewal and near-surface turbulence (Jähne et al.1987),which are affected by surfactants (Frew 1997) as well as wind forcing. In particular, small-scale waves (small gravity and capillary waves) are believed to play a primary role in promoting gas exchange,and some of the scattering properties of these waves are observable with space radar sensors (scatterometers and altimeters). One focus for future efforts should be understanding the relationship between radar backscatter from small-scale surface waves and the transfer velocity. This work will require the complementary use of satellite altimeter and scatterometer data to increase spatial and temporal coverage,as well as in situ studies to develop appropriate equations relating transfer velocity and surface roughness. An essential complement to satellite estimates of net carbon fluxes comes from atmospheric O_2/N_2 data. These provide a fundamental constraint on seasonal new production (that portion of primary production that does not represent internal mixed-layer recycling) on a hemispheric or basin scale, and the interannual variability in these rates.

Current estimates of mean ocean primary production must be improved at basin to global spatial scales and daily to interannual temporal scales. Satellite-derived fields of near-surface phytoplankton chlorophyll concentrations are essential to developing the calculations and models needed to do this (Behrenfeld and Falkowski 1997). An essential focus of this work should be the assessment of new production. New production is more closely related to the net flux of CO_2 from surface to deep waters than is total primary production. The relationship between new production and net primary production is not a simple proportionality. Estimating new production requires knowledge of nutrient budgets of surface water, as well as net primary production. Direct measurement of nutrient concentrations is not possible from space,but sometimes concentrations of major plant nutrients such as nitrate can be related by regression to sea surface temperature on regional scales (e.g.,Kamykowski and Zentara 1986). Mineral aerosols are one of the primary sources of iron and other trace elements that limit new production and net primary production in some important ocean regions,including the Southern Ocean. Aerosol plumes and sea surface temperatures are both detectable by space sensors.It may therefore be possible to use satellite data to help quantify nutrient budgets in the upper ocean,and hence rates of new production.

Advanced ocean color sensors will help improve estimates of global primary production. For example,the satellite MODIS (Moderate Resolution Imaging Spectrometer) and MERIS (Medium Resolution Imaging Spectrometer) will provide estimates of chlorophyll fluorescence,which can then be used to estimate phytoplankton quantum efficiency or at least the phytoplankton photoadaptive state. The additional spectral bands and higher signal to noise ratio of these advanced sensors will also provide some capability to distinguish phytoplankton functional groups and thus some capability to classify ocean ecosystem structure on large scales.

Several advanced ocean color sensors are planned by NASA and other international space agencies for the next five years, but plans are very uncertain for the post-2005 timeframe. By the end of the next decade, basic ocean color measurement capability may be transferred to operational satellites (e.g., the NOAA/DOD/NASA National Polar-Orbiting Operational Environmental Satellite System, NPOESS,project), but it is not clear if the full capabilities anticipated from MODIS and MERIS will continue beyond the middle of the next decade. Cooperation and coordination among international space agencies should be encouraged to ensure the continuing remote-sensing capabilities required to support future carbon research programs.

Goal 3: Assessing the Role of Land Use

Chapter 2,in its final section,discussed the importance of land use to the overall carbon cycle,as well as to understanding the time history and spatial distribution of carbon sources and sinks. Goal 3 of the CCSP is therefore to establish accurate estimates of the impacts of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales. The following are the major program elements and activities proposed to move toward this goal.

Goal 3: Major Program Elements and Activities

- Document the history of agricultural expansion and abandonment and its impact on the contemporary carbon balance of North America. Conduct intensive historical land use analyses across environmental gradients, in coordination with the proposed North American network of eddy flux measurement sites.

- Improve observational capabilities in tropical regions through cooperation with tropical nations, including international expeditions and exchanges and training of scientists and managers.

- Apply the observational programs discussed under Goal 1 in the tropics, including long-term observations and modeling.

- Couple socioeconomic analysis of land management strategies with biogeochemical models to evaluate the social and biophysical viability of future carbon sequestration options.

The emphasis of the proposed program elements and activities is the tropics and North America. As discussed in the final section of Chapter 2,the tropics are important because of the magnitude of the postulated deforestation source in this region. The focus on North America complements the proposed terrestrial sink program element by providing information on the history of the observation sites.

The data needed to construct reliable land use histories have temporal and spatial gaps over large parts of the world. In the tropics particularly, the expansion of cropland, much of it unrecorded,is presumed to be a major contributor to deforestation (FAO 1995). The unrecorded tropical cropland expansion tends to be highly fragmented,making its monitoring by remote sensing difficult with all but the highest resolution sensors. Afforestation in the Northern Hemisphere mid-latitudes is a significant component of the Northern Land Sink, yet there is a lack of uniformity in the criteria used to enumerate afforested area and define associated carbon flux densities (Nilsson and Schopfhauser 1995). A major effort is needed to assemble land use histories for both tropical deforestation and Northern Hemisphere afforestation. The basis for such histories includes a variety of potential data sources (e.g.,national censuses,provincial and local land use surveys and tax rolls, remotely sensed imagery, and proxy measures such as changes in local population and technology regimes). These land use histories must be spatially explicit (of county-level or finer resolution, depending on data availability) and should extend as far back in time as needed to capture the current impacts of past disturbances on carbon fluxes in a particular region.

A wide range of historical data have been applied to the estimation of CO_2 emissions from land use (e.g., Houghton et al.1983,Melillo et al.1988, Foster 1993). Recent progress has focused on the merging of many kinds of historical records with satellite-derived measures of land cover, and on the use of increasingly sophisticated models of ecosystem response (e.g., Foster 1995). This approach constrains historical reconstructions to be consistent with the geographic distribution of current land cover, and provides the spatial resolution needed to test hypothesized sources and sinks. As high-resolution atmospheric sampling continues and expands in the future, records of CO_2 and its stable isotopes,combined with records of ^{14}C,CH_4, and other indicators of particular land use effects (e.g., N_2O),will become increasingly valuable as historical constraints.

Of particular concern in reconstructing historical emissions is the question of a pre-agricultural steady state. Although ice core records indicate that the global CO_2 budget was near a steady state for thousands of years before the 19th century, this evidence does not assure that particular regions were not net sources or sinks for carbon. For example,several studies have suggested that high-latitude soils were still sequestering carbon as part of their recovery from the most recent deglaciation (Billings et al. 1982,Harden et al. 1992). Estimates of human emissions typically assume a pre-agricultural steady state (e.g., Houghton 1993), whereas direct assessments of CO_2 fluxes may reflect local non-steady-state effects. Thus,integration of emissions estimates and flux observations must include cautious consideration of steady-state assumptions.

Estimates of human CO_2 emissions must account for CO_2 fluxes associated with materials removed to locations other than the sites of original growth or burial. The need

to account for the fate of forest products is widely recognized (Houghton et al.1983). However, confusion persists about what oxidation of products from previous harvests should be reported in accounting for the net effects of forestry activities (Houghton 1993). Recently, Stallard (1998) has suggested that eroded soil carbon constitutes another "off-site" form of carbon that must be explicitly included in carbon budgets. Because agricultural activities are known to have vastly increased historical rates of erosion in northern temperate latitudes,the fate of eroded carbon is directly relevant to testing the Northern Land Sink hypothesis.

Goal 4: Improving Projections of Future Atmospheric CO_2

Better projections and information are needed to meet future societal needs:

Goal 4: Major Program Elements and Activities

- Improve representation of physical and biological processes in models of the carbon cycle to reflect observations and new knowledge more accurately.

- Provide a framework for rigorous analysis of observation and independent comparisons and evaluations of climate and carbon models using comprehensive data and both formal and informal model assessment activities.

- Develop new generations of terrestrial biosphere and ocean carbon exchange models, including the roles of both natural and anthropogenic disturbances, succession, and the feedbacks through climate change and anthropogenic perturbations to carbon dioxide and nutrients.

- Develop coupled earth system models incorporating terrestrial and oceanic biogeochemical processes in climate models of the atmosphere and ocean.

- Predictions the future evolution of CO_2 concentrations, for use in evaluating the consequences of societal decisions.

The foundation for predicting future changes in the carbon cycle is understanding the mechanisms that regulate it,the way those mechanisms respond to environmental changes,and the ways those mechanisms interact. Like current understanding,advances in the future will be based on a combination of observations,manipulative experiments,and synthesis via models. Useful models will range from qualitative conceptual models to schemes for connecting or extrapolating observations,to simulations of multifactor processes. Models based on all these approaches can provide powerful tools for asking "what-if" questions about the consequences of future events. Manipulative experiments can provide a mechanism for direct tests of critical model predictions at a range of spatial and temporal scales.

Models

The following provides an overview of the types of models and experiments needed for prediction,including the necessary scientific foundations for credibility.

Models for Data Analysis. A vast array of observations of the natural carbon cycle and results from experiments that manipulate controlling variables will emerge from the proposed program. Models designed for data assimilation and analysis represent a critical step in developing more refined experiments.Inverse and diagnostic models (the latter used to probe data sets) are the bridge between the data collection,conceptual understanding, and predictive models. For example,tracer transport models use atmospheric observations to test rates of transport derived from general circulation models (GCMs) or assimilated meteorological fields. Inverse models use atmospheric and oceanic observations of concentrations to estimate surface fluxes,providing a test for hypotheses about the time-space variability of fluxes.Inverse modeling thus forms a link between data,theory, and prediction,providing constraints on today's fluxes that should be consistent in models of the potential future.

Advanced Component Models and Scaling. Process and theoretical studies lead to new understanding and,in turn,improvement in model output,as mechanisms are incorporated into models. The impact of processes on the whole system must be evaluated by comparing the improved models to earlier formulations and to observations,and by conducting sensitivity analyses to determine their importance.

Some new scientific results must be scaled in time and space. For example, the rectifier effect (again, the covariance between diurnal and seasonal cycles of CO_2 net exchange and rates of atmospheric mixing) can be understood by micrometeorological and plant physiological theory. However, as it occurs on finer spatial and temporal scales than those resolved in global models, an approach for aggregating the effects of the rectifier has to be developed. Similarly, the biochemical effects of CO_2 on photosynthesis have been understood for over a decade, but the impact on long-lived, whole plants, plant communities, and ecosystems is unclear. To achieve the objectives listed for Goal, 4 a vigorous program linking process studies to modeling must be maintained for the

new science to be incorporated in local and global predictive models.

Models for Decision Analysis. The great majority of terrestrial systems are currently managed. Management choices have implications for carbon storage (e.g., choices such as no-till agriculture, fire suppression, length of forest harvest rotation, and fertilization). Carbon storage is one factor to consider in making land management decisions, and reliable tools are needed for evaluating the carbon storage consequences of various land management scenarios. There is an urgent need for local- or regional-scale models in agriculture, forestry, urban ecosystems, and marine systems that can be used to evaluate the effects of specific interventions (e.g., no-till agriculture, deep ocean CO_2 injection) to enhance carbon storage, along with assessing associated environmental and economic consequences. These models will form a link between the basic science of the carbon research community and the needs of stakeholders and decision makers.

Carbon System Models and Carbon-Climate Models. The carbon system is intimately coupled to the physical climate system. Indeed, the focus on carbon derives from the role of CO_2 as a greenhouse gas. To project the large-scale consequences of changes to the carbon cycle, it is necessary to link knowledge of the carbon system to that of the climate system. For example, if enhanced concentrations of greenhouse gases disrupted oceanic circulation, the ocean carbon system could be affected by changes in both physics and biology. These changes would help shape the effect of any anthropogenic increase in CO_2 emissions on atmospheric concentrations, thus modulating the climate response.

Similarly, feedbacks could occur through terrestrial systems, with terrestrial carbon exchange possibly modified by climate then affecting atmospheric CO_2, in turn modifying the climate impact of any given anthropogenic emission scenario. These feedbacks are presently uncertain, depending on the rate, magnitude, and spatial distribution of climatic changes. For example, if climate changes are greatest in peatlands at high latitudes, CO_2 emissions would likely increase. More equable warming could result in either increases or decreases of carbon storage in the terrestrial biosphere.

To analyze the potential effects of future industrial and land use emission scenarios, Earth system models are required that couple physical models of the atmosphere, ocean, and cryosphere to biogeochemical models of terrestrial and marine ecosystems. Earth system models predict partitioning of emissions of CO_2 (and other greenhouse gases) between the mobile terrestrial, oceanic, and atmospheric reservoirs, and then predict climatic response and the effects on biophysical processes in the land and ocean.

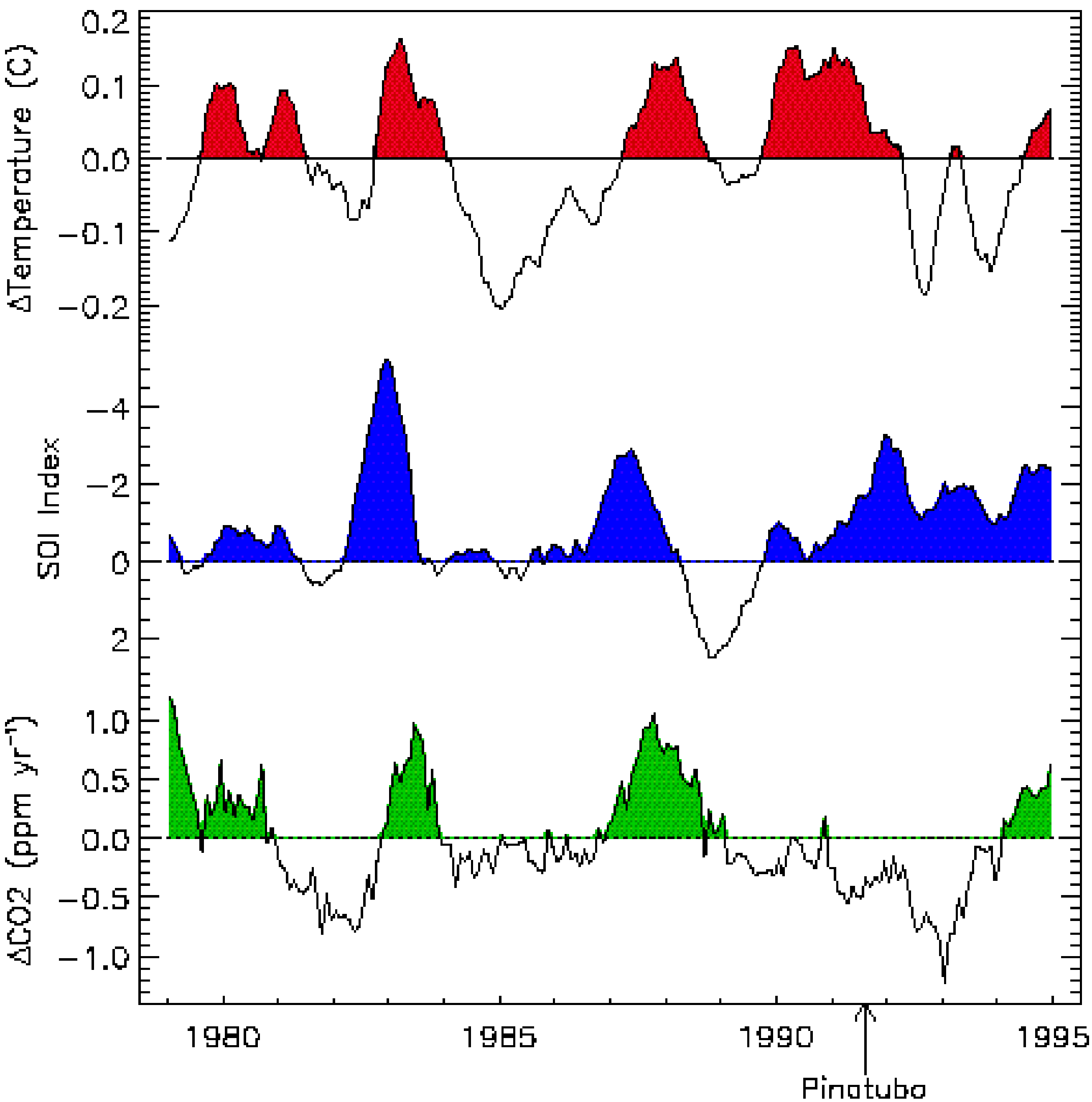
Earth system models build on the knowledge of mechanisms gained in process studies and advanced component modeling studies, and on the evaluation of knowledge derived from diagnostic studies and historical and paleorecords. They will allow us to examine questions about the relationships among policy choices, sources and sinks, and resulting concentrations. These models demand rigorous examination of knowledge, extensive computing resources, and sustained efforts of testing and refining using integrated knowledge from the Carbon Cycle Science Program overall.

All of the above models must be painstakingly compared to observations, requiring strong commitment to testing and refining models. It can be very difficult to test large-scale models against real data sets, obtained in specific locations and at specific times. A coordinated effort to promote rigorous comparisons of models and measurements is needed on the part of the agencies involved in the CCSP.

Experiments

Experimental studies on the future of the terrestrial carbon cycle should be used to probe controlling processes, especially when the nature of the controls may be obscured by spurious correlations or long time constants. These studies should explore the behavior of key mechanisms to forcing outside the range of current ambient conditions, and evaluate responses to forcing from simultaneous changes in multiple environmental and ecological factors. In addition, well-designed experiments can be powerful tools for making results from carbon cycle research accessible to a broad range of stakeholders. Manipulative experiments are, however, complements to models, not full alternatives. The processes controlling the future terrestrial carbon cycle operate over a broad range of spatial and temporal scales. Many processes with the potential to dominate future changes in terrestrial carbon storage—for example, changes in the tree species that dominate forests or changes in the frequency of wildfire—are beyond access through short-term, small-scale experiments. Even if it were feasible to make an aggressive commitment of resources to work at greater temporal and spatial scales, manipulative experiments lose their utility as the time scale of the experiment merges into the tempo of global changes, the far from fully replicatable grand experiment at the global scale.

Manipulative experiments can provide powerful access to key uncertainties about the future trajectory of the global carbon cycle. However, many aspects of the terrestrial carbon cycle are very difficult to study with manipulative experiments. Consequently, the research targets need to be selected with careful attention to the likely importance of the focal processes, the efficiency with



Interannual variations in temperature, the Southern Oscillation Index (SOI) (which correlates with El Niño cycles), and the growth rate of CO_2. Recent work has suggested that observed variations in the growth rate of atmospheric CO_2 may bear the signature of climate effects on ecosystems and the oceans. Understanding the mechanisms that have caused global terrestrial and ocean carbon exchange to vary over the period of observation provides a vital test for the "scaling" of process level knowledge and a basis for predictive modeling.

which the experiments probe these processes,and the feasibility of obtaining the critical information using other approaches. In addition, experiments must be designed for effective integration with observational studies and models. The following approaches should be pursued and enhanced.

Natural Experiments. Frequently, nature presents a ready-made experiment,providing investigators an opportunity to study ecosystem responses to a major environmental forcing. Natural experiments are often permanent or at least persistent features of the landscape,allowing unique access to responses with long time constants,usually with little or no cost for maintaining the natural manipulation. Recent studies with ecosystems near natural CO_2 vents are a good example of the applicability of these features for understanding the future of the global carbon cycle (Raschi et al.1997). The Hawaiian lava flows with a range of different ages and local climates represent a parallel example for basic ecological research that is fundamentally relevant to the carbon cycle (Chadwick et al. 1999,Torn et al.1997).

Natural experiments are invaluable links between long-term observations and purposeful manipulations. They are natural system analogs of research designed to take advantage of recent patterns of land use change. Because these experiments provide unique opportunities to observe long-term,and sometimes large-scale, responses to controlling factors,they should receive greater emphasis. Natural experiments that should be evaluated include not only CO_2 vents and gradients of substrate age,but also steep,topographic gradients of temperature and precipitation, geothermal features,and sites with unusual flora and fauna as a result of isolation. Natural experiments form a continuum with gradient studies. Some of the most powerful uses of the natural experiment approach may lie in combining common gradients with much less common natural experiments.

Multifactor Manipulations. Results from global change experiments are often difficult to interpret in more general terms. Ecosystems targeted by different experiments typically differ in a number of features,creating a barrier to partitioning control for the different responses among the different features. Multifactor manipulations can play a critical role in enhancing the foundation for generalization and reducing uncertainties about future responses. The next generation of multifactor experiments should address two kinds of questions. First,how do ecosystem-scale responses to global change components change when the global changes occur in combination? Experiments should consider interactions among elevated CO_2, warming,and altered levels of precipitation,nitrogen deposition,and ozone. Second,how do the characteristics of ecosystems themselves affect response to global change? A new generation of experiments should focus explicitly on the way that differences in ecosystem characteristics influence responses to global changes. For example,matched manipulations on substrates of different age or with ecosystems of different biological diversity can greatly enhance the ability to generalize. Some of these experiments should focus on the interface between land use and atmospheric change,with manipulations of CO_2, temperature,and other environmental factors at sites of different ages since disturbance, with different management practices,and with different levels of anthropogenically stimulated biological invasion. Multifactor experiments should address a broad range of mechanisms that may influence future carbon storage. These mechanisms range from direct responses of plant growth,to enhanced success of one or more plant or microbial species,to altered decomposition,to changes in sensitivity to fire,pests,or pathogens. Integrating results from these multifactor experiments in models and general interpretations will present many challenges,but it is much wiser to confront the challenges than to ignore the processes to which these experiments provide unique access.

Experiments with Model Ecosystems. The agenda of multifactor experiments is challenging,complex,and essential. Many of the processes that may play critical roles in ecosystem responses have large spatial scales and long response times. This circumstance places a high priority on optimizing the trade-offs between experimental tractability and relevance to the ecosystems with the largest potential impact on the carbon cycle. As in many fields of science,progress can be rapid if a sizeable fraction of the resources is invested in studies on experimental models. These are systems chosen with an emphasis on tractability and access to the key processes,and with much less emphasis on the model system's quantitative contribution to the global carbon cycle. For example, studies on annual grasslands can address multiple global change factors while allowing reasonable replication and large numbers of individuals per replicate. For other purposes,studies on artificial ecosystems in meso-cosm facilities may provide a useful balance of tractability and relevance. With sufficient resources and planning,useful experiments on model systems might operate on a large scale,addressing, for example,the relative success of grassland species and rapidly growing trees under a range of manipulations.

A research program with an emphasis on model systems will require careful planning and coordination across experiments. Scaling interpretations from the models to the systems with the most direct relevance to the carbon cycle may require experiments deliberately designed to address uncertainties in the scaling. In the longer term, we should expect a continuing iteration among experiments, observations, and models. Evidence from one of these approaches will receive added value from extension across

the others, and hypotheses suggested by one approach will be tested by evidence from all three approaches.

Goal 5: Evaluating Management Strategies

Goal 5: Major Program Elements and Activities

- Synthesize results of global terrestrial carbon surveys, flux measurements, and other relevant results, and use this analysis to develop the scientific basis for management strategies to enhance carbon sequestration.

- Determine the feasibility, environmental impacts, stability, and effective time scale for capture and disposal of industrial CO_2 in the deep ocean and in geological reservoirs.

- Define potential strategies for maximizing carbon storage that simultaneously enhance economic and resource values in forests, soils, agriculture, and water resources.

- Identify the criteria to evaluate the vulnerability and stability of sequestration sites to climate change and other perturbations.

- Document the potential sustainability, lifetimes, and interannual/decadal variability of different managed sequestration strategies.

- Provide estimates of the uncertainties related to managed sequestration that are required for policy discussions and decisions.

- Develop the monitoring techniques and strategy to verify the efficacy and sustainability of carbon sequestration programs.

- Create a consistent database of environmental, economic, and social performance measures for the production, exploitation, and fate of wood and soil carbon "from cradle to grave" (for wood, from stand establishment through final disposal; for soil carbon, from formation through burial).

- Develop and parameterize an analytic framework for predicting and evaluating management and policy alternatives considering material transfer, economics, societal factors, wastes and emissions, raw material, labor and energy inputs, carbon sources, sinks, and fluxes, and output for mass carbon balance.

Human land use may be directed toward enhancing terrestrial carbon sinks through a variety of management options. Focusing on the United States, such options include manipulation of forestry practices (such as harvest dynamics, and pest and pathogen control) and agricultural land management practices (such as tillage, crop rotations, and fertilizer use; see Lal et al. 1998). To evaluate the potential of management strategies to sequester carbon, there must be improved process understanding of the relationships between changes in land cover and biophysical controls of carbon exchange. One way to gain such understanding is the close coupling of historical information on land use with eddy-correlation experiments across a network of sites encompassing large temporal and spatial variability of fluxes and land uses (beginning with the AmeriFlux network). The land use information is needed to infer historical ecologies (e.g., species composition, soil organic matter dynamics) that help explain current carbon fluxes. Where possible in this network, experimental designs should allow for the observation of the effects of alternative management strategies (e.g., fire suppression, age-selective forest harvesting). Efforts should be made to ensure that new tower sites have highly variable land use histories. This will broaden the base of knowledge from which to project future fluxes. Further coupling of land use and carbon flux information with biogeochemical models, such as those participating in the Vegetation/Ecosystem Modeling and Analysis project (VEMAP), may be used to predict carbon uptake by whole ecosystems.

Results from the U.S. Forest Service Forest Inventory Analysis (FIA; Schroeder et al. 1997), of periodic measurements of wood volume on thousands of plots of land classed as "forest," indicate lower values of net carbon accumulation in forests (about 0.3 Gt C/yr) for North America than are inferred from inverse analyses (0.9 to 1 Gt C/yr) or tower flux data (~0.7 Gt C/yr). However, the FIA data set has not been optimized nor sufficiently analyzed as yet to ensure that the estimated rates for net carbon sequestration derived from it are accurate. The focus has been to define the wood volume potentially available for harvest. Thus, wood volumes on land reclassified as nonforest and wood harvested as forest products are both removed from the inventory, but a very large quantity of this wood may remain in the form of wood for long periods. Properly accounting for such "removals" in the carbon budget should increase corresponding estimates of net carbon sequestration by 50 to 100 percent. In the CCSP, we propose broadening the FIA to incorporate an explicit focus on carbon, including upgrading the sampling scheme, increasing the number of parameters measured, and increasing the frequency of measurements.

In deep ocean sequestration of CO_2, industrial CO_2 recovered from fossil fuel power plants may be injected directly into the deep ocean for disposal. This arrange-

ment would circumvent the slow natural transfer rate of CO_2 from the surface to the deep ocean. Laboratory studies and in situ experiments show that liquid CO_2 is denser than seawater at water depths below about 3,000 meters. Additionally, rapid growth of CO_2 hydrate crystals along the water-liquid CO_2 interface has been observed. Thus, liquid CO_2, when piped onto the seafloor, is likely to settle there and be quickly transformed into solid hydrate forms. The liquid CO_2 and the hydrate crystals dissolve gradually into the overlying seawater and mix into the surrounding deep sea. The retention time of CO_2 in the deep ocean depends on ocean transport and chemical processes such as neutralization reactions with calcareous sediments. Once the water returns to the ocean surface, some CO_2 can escape back to the atmosphere. Hence, disposal in relatively isolated regions of the ocean is preferred because of longer retention times. The effects of acidified seawaters on benthic ecosystems must be evaluated before any large-scale disposal can be contemplated. Near-field as well as far-field distributions of CO_2 around a disposal site must be investigated. The scientific investigations outlined in the CCSP, such improvements in ocean general circulation models (GCMs), will be directly applicable in evaluating CO_2 sequestration in the oceans.

Not all management strategies will be economically viable or socially acceptable. For example, over the long run, a rising global demand for timber products may provide a strong inducement to keep forest harvest cycles shorter than the optimal time for sequestering the greatest amount of carbon. Collaboration among biogeochemical modelers, and economists and other social scientists will be necessary to examine the economic efficiency and social desirability of various management strategies. Such collaboration will require information flows across a permeable boundary between the initiatives proposed in this plan and associated work in the human dimensions research community.

Observing and Discovering

An essential complementary perspective to testing defined hypotheses is suggested by the second central scientific question for the CCSP: "What will be the future atmospheric CO_2 loading resulting from both past and future emissions?" It is very difficult to frame this question within the context of a single hypothesis or even a framework of closely linked hypotheses. Scientists must look toward the future with considerable humility, bearing in mind the significant uncertainties involved in identifying the processes responsible for a carbon sink as large as the hypothesized Northern Land Sink, or in trying to predict how the ocean sink may develop over time. Some issues concerning future carbon cycling can be addressed through such hypotheses as the Increasing Ocean Inventory. It is also possible to formulate alternative assumptions as competing hypotheses for carbon cycling in the future, but none stands out as pervasively important or useful in the sense that the Northern Land Sink and Increasing Ocean Inventory hypotheses dominate current studies. Questions about future atmospheric CO_2 levels highlight the need for a comprehensive and balanced program of observations, manipulative experiments, and models. These must contribute to the focused testing of hypotheses while remaining comprehensive enough to entrain the new ideas and discoveries that will guide hypotheses for the future. Through testing current hypotheses, unforeseen questions, as well as answers, will surely emerge.

In particular, current attempts to project the future require assumptions and speculation that extend well beyond the range of issues of any program focused on presently testable hypotheses. A future could be hypothesized for atmospheric CO_2 based on reasonable emissions scenarios, consistent with the notion that future trends will follow the pattern of past trends (in biological and ocean uptake, emissions, etc.). However, this assumption encompasses many untested hypotheses. For example, the IPCC scenarios for future CO_2 levels are based on models that have been calibrated using a "fertilization effect" to account for the past and present "missing" carbon sink. Yet this effect is just one of many proposed mechanisms for terrestrial carbon uptake, and large-scale efforts to test it are just beginning. It is unknown how stable terrestrial uptake mechanisms are; the fertilization effect might be expected to continue for much longer than some other contributing mechanisms, such as reforestation in the United States and Europe. Likewise, the IPCC CO_2 scenarios depend on ocean models that assume a steady climate. These assumptions seem increasingly precarious as more is learned about the interplay between oceanic and atmospheric dynamics, and as the prospect of significant changes in the global climate system become more likely. Clearly, even as the scientific community works toward resolving uncertainties through focused hypothesis testing, strong action is necessary to assure that new ideas and discoveries continue to help solve questions about the future behavior of the Earth system.

As this report has made clear, an essential component of the research strategy is a sustained observational effort. This endeavor should provide improved, quantitative estimates of natural and anthropogenic carbon distributions, sources, and sinks, and their temporal and spatial variability at regional as well as global scales. Efforts to develop more focused studies of particular problems, or tests of particular hypotheses, should not obscure the need to continue and expand a program of comprehensive basic observations, with parallel modeling to assimilate the data. Because these observations will be useful in assessing carbon sequestration activities, policy needs must be treated with utmost attention during planning. The design and implementation of such a program,in a cost-effective manner and in concert with the international research community, is a major task.

In addition to a program of comprehensive observations,support is suggested for four types of studies outside the realm of programs to test current hypotheses. Because all these study types are inherently innovative, they are defined by example here, rather than by descriptions that might prove too restrictive.

Studies That May Anticipate "Surprises." Some studies may help reveal unexpected interactions between the global carbon cycle and the climate system. Recent studies of paleoclimate have revealed the past occurrence of surprising short-term instabilities in the Earth's climate system. Concerns about instabilities in future climate must be extended to the potential effects of these instabilities on carbon cycling.

An example of one such surprise was the finding of coupled atmosphere-ocean simulations of climate change, which predict large increases in the vertical stratification of the ocean with warming in lower latitudes and freshening in higher latitudes. These changes would lead to large reductions in ocean thermohaline circulation as well as in vertical mixing in general (Manabe and Stouffer 1994). The impact of these changes on ocean biology would likely be extremely large. The effects on the air-sea balance of carbon are difficult to predict,,because of the counteracting effects of slowed circulation and a potentially more efficient biological pump taking up a higher fraction of surface nutrients (Sarmiento et al.1998).

Climatic warming appears to promote carbon storage in mid-latitude forests,but possibly to promote release of much larger stores of organic carbon from boreal forests and peatlands through increased rates of fire and mineralization (Goulden et al.1998,Kasischke et al.1995)

Studies That Suggest Innovative Hypotheses or Ideas. Creative ideas often do not fit preconceived hypotheses or priorities. Important new concepts may arise from unexpected sources,often from scientific subdisciplines not normally associated with carbon research.

A recent paper (Stallard 1998) uses evidence from geomorphology and sedimentology to hypothesize that large amounts of carbon may be buried on land as a result of enhanced erosion and subsequent deposition accompanied by fertilization associated with cultivation. This study has focused attention on the need to account for the fate of large quantities of eroded soil carbon.

The hypothesis that iron might play an important role in oceanic photosynthesis has a long history. However, the first trustworthy in vitro tests of the hypothesis had to await the development of accurate techniques for measurements in seawater (Martin 1991). Recent in situ iron fertilization experiments provide dramatic support (Coale et al.1996) for the bottle experiments. It has been hypothesized that iron supply played an important role in the changes of atmospheric CO_2 content of the last ice ages (Martin 1990). Iron also also appears to be a major factor in nitrogen fixation in the low-latitude surface ocean (e.g.,Karl et al.1997,Michaels et al.1996a,Michaels et al.1996b). A major source of iron to the ocean is dust delivered through the atmosphere. One notable question that has arisen,then,is whether changes in dust transport that accompany climate change could affect oceanic photosynthesis.

Studies of Past Geologic Variations in the Carbon Cycle. It is widely recognized that the global carbon cycle has varied in the geologic past. Analyses of gases sampled from ice cores have shown that atmospheric CO_2 and CH_4 concentrations varied in concert with the pronounced fluctuations between glacial and interglacial climatic conditions over the past several hundred thousand years (Barnola et al.1987,Stauffer et al.1988, Jouzel et al. 1993). Larger past CO_2 variations—comparable to those anticipated from future human activities—have been inferred from models based on the geologic record of the last 100 million years and longer (Berner 1994). Many of the processes involved in these changes are so slow that they have little relevance to time scales of usual human concern. However, the geologic record is a vital source of information about the dynamic nature of carbon cycling and its interactions with the global climate system over a broad spectrum of time scales. Geologic research can provide important and unexpected insights that are directly relevant to the principal questions addressed in this science plan.

Measurements from the paleorecord suggest that exchanges between reservoirs of the carbon system are not static on millennial time scales. For example,analyses of an ice core from Taylor Dome,Antarctica,show that atmospheric CO_2 concentrations changed over time during the Holocene,with a steady increase from 260-280 ppm over a period of 7000 years (Indermühle et al.1999). These changes may have been due to changes in the amount of terrestrial biomass and/or ocean CO_2 storage. Numerical models of anthropogenic CO_2 generally assume that a steady state existed before human influence. This assumption appears to be reasonable for global models because the rate of CO_2 change during the Holocene was very slow compared to the anthropogenic CO_2 perturbation. However, the changes indicated by the ice core data may be quite significant for studies of carbon budgets on a regional scale,because the inferred imbalances in the carbon cycle are not likely to have been uniformly distributed over the Earth's surface.

Using precise correlations among ice and sediment cores,paleoclimatologists have shown that the most recent glacial cycles were punctuated by large and extremely abrupt climate events (of years to decades)

(Blunier et al.1998,Dansgaard et al.1993). Many of these rapid events appear to correlate with abrupt changes in atmospheric methane (Brook et al.1993,Chappellaz et al. 1993),and some may have been associated with modest changes in atmospheric CO_2 (Stauffer et al.1998). Thus, even on time scales of years to decades,there is geologic evidence of close interaction between climate and the carbon cycle. The evidence suggests that atmospheric methane may be a more sensitive indicator of certain changes than atmospheric CO_2.

Studies of the "Human Dimensions" of Future Carbon Cycle Trends. Future terrestrial carbon budgets will be strongly influenced by human land use. The best attempts to forecast future trends may be confounded by uncertainties about future human activities that are influenced by factors beyond the usual scope of scientific interests in carbon cycling.

Future rates of tropical deforestation will depend largely on the expansion of regional agricultural capacity. Most of the developed countries,which are usually outside the tropics,will depend almost exclusively on technology-driven increases in productivity per unit land area to increase future capacity. In these countries,new changes in the amount of cropland in production are likely to be negligible.The developing countries will depend on a mix of increases in productivity along with expansion of cropland to increase future capacity. Excluding China,these countries have about 2.5 billion hectares of land on which rain-fed crops could give reasonable yields,with approximately 80 percent of it in tropical Africa and Latin America (FAO 1995). Much of the deforestation taking place in the tropics is the result of the disorderly, unrecorded expansion of cropland (FAO 1995). The FAO (1995) projects that deforestation from this unrecorded expansion of cropland will not only likely continue,but will probably do so at a rate exceeding that required to meet national agricultural capacity targets. Quantification of rates of unrecorded conversion of tropical forest to cropland is a critical need for projecting future rates of deforestation.

Expected Results

The ultimate goal of the U.S.CCSP is to provide the scientific understanding required to predict future concentrations of atmospheric CO_2 and evaluate alternative scenarios for future emissions from fossil fuels,effects of human land use,sequestration by carbon sinks,and responses of carbon cycling to possible climate change.

These issues are addressed by Goals 4 and 5—improving projections of atmospheric CO_2 through complementary methodologies and by incorporating regulating mechanisms,and developing a scientific basis for carbon sequestration management strategies. Achieving these two goals will permit us to carry out several critical tasks:

- Present a new generation of models, rigorously tested using time-dependent,three-dimensional data sets,suitable for predicting future changes in atmospheric CO_2.
- Develop management and mitigation strategies that optimize carbon sequestration opportunities using terrestrial ecosystems,primarily forest and agricultural systems,in addition to evaluating the efficiency of ocean carbon sequestration.

Currently, estimates of terrestrial sequestration and oceanic uptake of CO_2 vary significantly, depending on the data used and the analytical approach (e.g., Forest Inventory Analysis,direct flux measurements in major ecosystems,inverse model analysis of CO_2 data from surface stations, changes over time of global CO_2, O_2, $^{13}CO_2/^{12}CO_2$, etc).

The proposed research program under Goals 1,2,and 3,will reconcile these estimates to a precision sufficient for policy decisions by providing new types of data and new, stringent tests for models and assessments. The specific deliverables from these three goals are as following.

Goal 1 is to establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the underlying mechanisms that regulate it.

- Define the existence and magnitude of past and present terrestrial carbon sinks.
- Elucidate the impacts of climate variations (e.g.,length of growing season,soil moisture,long-term temperature changes),of fertilization (CO_2, NO_x, etc.),and of land use changes on atmospheric CO_2.
- Document and constrain uncertainties related to the potential Northern Hemisphere terrestrial carbon sink.

Goal 2 is to establish accurate estimates of the oceanic carbon sink and the underlying mechanisms that regulate it. In the near-term,the focus will be on the North Atlantic and North Pacific oceans to best complement the terrestrial focus on the Northern Hemisphere and tropics.

- Incorporate better understanding of ocean processes in currently undersampled regions,such as the Southern Ocean,into general circulation models (GCMs).
- Determine the existence,magnitude, and interannual variability of oceanic carbon sinks and sources on a regional scale through assimilation of new observations.
- Explain observed changes in the ocean carbon sink due to variations in circulation and biological and chemical changes using enhanced models tested rigorously against new observations.
- Incorporate improved oceanic CO_2 flux estimates to improve constraints on inverse models for estimating

terrestrial sinks.

Goal 3 is to establish accurate estimates of the impacts of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales.

- **Document the existence,location,and magnitude of carbon sources and sinks resulting from historical and current land use changes and land management practices in critical regions.**
- **Provide improved assessments of the uncertainties related to land use,particularly for agriculture in North America and the tropics.**

The results of all the studies under goals 1 through 5 will be communicated to the public and policy makers in papers published in peer-reviewed journals.